Transition Between Transient and Steady-State Wear in the Sliding of Poly(phenylene sulfide) Against a Tool Steel Counterface

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ABSTRACT: Polyphenylene sulfide (PPS) powders in a grit size of 200 mesh were made into slab specimens in a size of 35 mm × 30 mm × 6 mm by compression molding. The friction and wear behaviors of PPS sliding against a tool steel counterface was studied in a pin-on-disk configuration, with changes in the test parameters, such as load, sliding speed, and counterface roughness. The morphologies of some typical transfer films were observed by optical microscope. The emphasis of this research was placed on the factors that affect the transition between transient and steady wear states. It was found that the transient friction and wear of PPS were significantly affected by initial counterface roughness, sliding speed, and applied load. The wear rate in the transient state increased with the increase in initial counterface roughness, and there was an optimal counterface roughness of 0.06 μm Ra for the minimum steady-state wear rate. A higher applied load led to a higher transient state wear, but did not necessarily lead to a higher steady-state wear unless the applied load was very high. Sliding speed had the greatest influence on transient friction and wear of PPS, particularly at high sliding speeds because of thermal effects. A very low sliding speed did not help in the development of transfer film and resulted in a high wear rate. At the medium sliding speed of 1.0 m s^{-1}, wear rate was the lowest because of the favorable condition for a uniform transfer film to develop during the transient state. © 1998 John Wiley & Sons, Inc. J Appl Polym Sci 69: 1099–1106, 1998

Key words: polyphenylene sulfide; friction and wear behaviors; transient and steady wear state

INTRODUCTION

The sliding wear state of a polymer can usually be divided into transient state and steady state. The research on the steady-state wear of polymers has been concentrated mostly. It has been found that many factors (such as counterface roughness, sliding speed, and applied load) affect the friction and wear behaviors of polymers. It has also been noticed that too high or too low a counterface roughness resulted in high wear, and often there is an optimal counterface roughness for minimum steady-state wear. Dowson and colleagues[1] reported that minimum wear occurred at 0.05–0.10 μm Ra for ultra high molecular weight polyethylene (UHMWPE) sliding against stainless tool steel under dry conditions. The corresponding value as reported by Buckley[2] was 0.37 μm Ra. Santner and Czichos[3] found an optimal counterface roughness of 0.2–0.3 μm Ra for minimum wear and coefficient of friction for polyamide 66, polyamide 6, polyoxymethylene, and poly(ethylene terephthalate) (PETP). Tanaka and colleagues[4,5] reported the counterface roughness of

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0.025 μm Ra for minimum wear of high-density polyethylene (HDPE) and low-density polyethylene (LDPE) sliding against tool steel counterface. For HDPE, the initial and steady-state coefficients of friction were found to decrease first and then increase with increasing counterface roughness. As for LDPE, the initial and steady-state coefficients of friction decreased initially with the increase in counterface roughness, but later remained constant. Yet, the reasons for this are not clear.[6] The optimal counterface roughness might be related to the formation of transfer film on the counterface. At too high or too low a counterface roughness, the uniform transfer film could hardly form. This is because the counterpart with a too-high surface roughness could abrade the polymer transfer film away from the substrate surface, whereas too smooth a counterface could hardly hold the transfer film to it.[7–9]

The effect of sliding speed on the friction and wear behaviors has been studied by a number of workers, but no general pattern has been found. Clarke and Allen[10] investigated the sliding wear behavior of various polymers under water-lubricated conditions. They found that steady-state wear increased with sliding speed for PETP, it increased first and then decreased for UHMWPE, and it decreased first and then increased for MoS_2-filled nylon 6. In dry sliding, the steady-state wear increased with sliding speed for UHMWPE,[11] poly(phenylene oxide) (PPO), poly(ether ether ketone) (PEEK), and polytetrafluoroethylene (PTFE).[12] The coefficient of friction did not change with sliding speed for PPO and PEEK, but increased for PTFE. The influence of sliding speed on the wear behavior is believed to be related to the strain rate and thermal effects at the sliding interface.[13]

Wear may be mild or severe, depending on the applied load. Because different polymers respond to load differently in terms of the coefficient of friction and wear,[3,10] further work is thus needed to understand the mechanisms that govern the changes in the friction and wear behaviors of polymers with the factors, such as load and sliding speed.

It should be noted that there is even less understanding of the transient state than the steady-state wear with respect to polymer tribology. Although the transient state lasts only a relatively short duration of the whole sliding process, it is still an important part of the friction and wear behaviors, because wear rate in the transient state is normally much higher than that in the steady state and the steady state is preceded by the transient state. Thus, the total wear loss after any sliding distance has more or less to do with the transient state wear that may or may not be significant in the context of its longevity, depending on the relative transient and steady-state wear values. The understanding of the processes in the transient state is also of fundamental significance, because the processes that occur in transient state contribute to steady wear state as well. This indicates that it is of both theoretical and practical significance to investigate the factors and the mechanisms that govern the transient friction and wear states.

In this article, both the transient and steady-state friction and wear behaviors of poly(phenylene sulfide) (PPS) under different test conditions were investigated, with more emphasis on the former.

EXPERIMENTAL

PPS slabs in a size of 35 mm $\times$ 30 mm $\times$ 6 mm were prepared by compression molding of PPS powders (grit size 200 mesh, supplied by Phillips 66 Company). Before molding, the PPS powder was dried at 250°C for 8 h. It was compacted in a compression molding machine to a pressure of 56 MPa and heated at a rate of 5°C min^{-1} to 310°C, and held there for half an hour. The pressure was raised to 28 MPa, because the pressure decreased considerably with the softening/melting of PPS. The mold was then cooled slowly down to room temperature and the molded block ejected. Rectangular pins of the size 5 mm $\times$ 6 mm cross-section and 25 mm long were cut out of the molded slabs to serve as the specimens for friction and wear tests. For the counterface, tool steel (compositions: 0.9% carbon and 1.6% manganese) disks of the size 5 mm thick and 75 mm in diameter were made. They were oil-hardened and tempered to a hardness of 58 HRc. The disks were ground and polished by abrasion against different grades of emery paper to provide varying values of the initial surface roughness. The polymer pins were also finished by abrasion against 320 grade emery paper. This ensured a good contact between the pin and the disk surfaces during sliding. Before the friction and wear tests, the pin and the disk were cleaned with soap, water, and acetone, respectively.

Sliding friction and wear tests were performed in a tribotester with pin-on-disk configuration. The tests were done under ambient conditions,

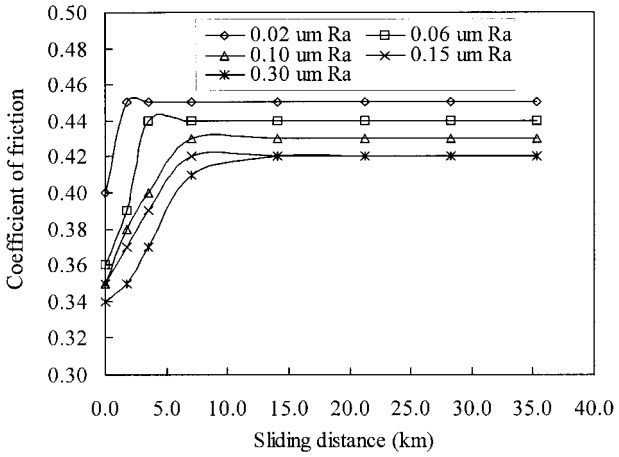

Figure 1 Coefficient of friction versus sliding distance for different counterface roughness (test conditions: sliding speed, 1.0 m s^{-1}; nominal pressure, 0.65 MPa).

with sliding speeds varying from 0.2 to 2.0 m s^{-1}, nominal pressures from 0.325 to 1.30 MPa, and disk surface roughness from 0.02 to 0.30 μm Ra. The polymer pin was held in a specimen holder on a loading arm that had two strain gauges to record the friction force. Wear loss was measured by weighing the pin to an accuracy of 10^{-8} kg at different sliding intervals, and the wear loss data were converted into volume loss by accounting for the density of PPS (1.36 g cm^{-3}). The steady-state wear rates were calculated from the slopes of the linear parts of wear loss versus sliding distance curves by the regression method, and the correlation coefficients were above 0.99. Three replicate friction and wear tests were performed for each condition and the coefficients of variation for the corresponding wear and coefficients of friction values were within 15%.

The morphologies of some typical transfer films were observed by the optical microscope, aiming at revealing the wear mechanisms of the composites under various conditions.

RESULTS AND DISCUSSION

Effect of Counterface Roughness on Friction and Wear

Figure 1 shows the plots of the coefficient of friction versus sliding distance for different counterface roughness. The variation of the steady-state coefficients of friction with counterface roughness is given in Figure 2. It is seen that the coefficient of friction started with a low value, but increased continuously during the transient state and finally reached a higher steady-state value. The lower the counterface roughness, the higher the steady-state coefficient of friction, except for higher counterface roughness of 0.15 and 0.30 μm Ra, wherein the coefficient of friction was the same. At the beginning of sliding, the coefficient of friction was lower because, in the absence of transfer film, the contact between the polymer pin and the tool steel counterface occurred only at high spots, so that the contact area was smaller. As the transfer film developed with increased sliding, the coefficient of friction rose with an increasing contact area. When a steady-state transfer film had been formed at the end of the transient state, the coefficient of friction also reached a higher, but stable value. In addition to the higher contact area, the reason for the higher coefficient of friction in the presence of transfer film could also be the higher cohesive forces acting between the identical PPS material in the transfer film and the pin surface.

As for the steady-state friction, the coefficient of friction for the counterface with lower roughness is slightly higher than that for the counterface with higher roughness. According to the adhesion law of friction, the coefficient of friction depends on the real contact area and the interface shear strength. Since the interface shear strength is the same for the same sliding pair materials, irrespective of the counterface roughness, the coefficient of friction depended mainly on the real

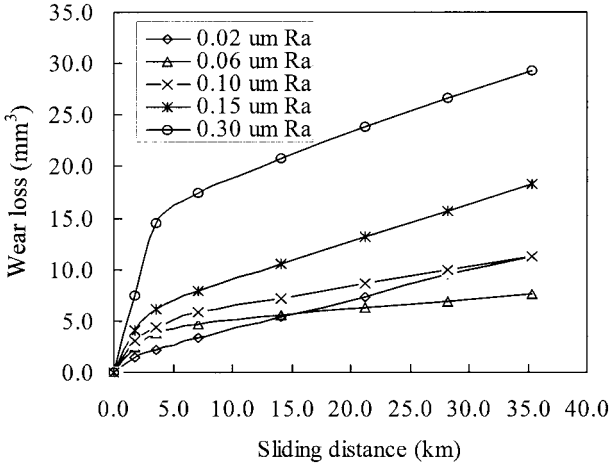

Figure 2 Steady-state wear loss and coefficient of friction versus counterface roughness (test conditions: sliding speed, 1.0 m s^{-1}; nominal pressure, 0.65 MPa).

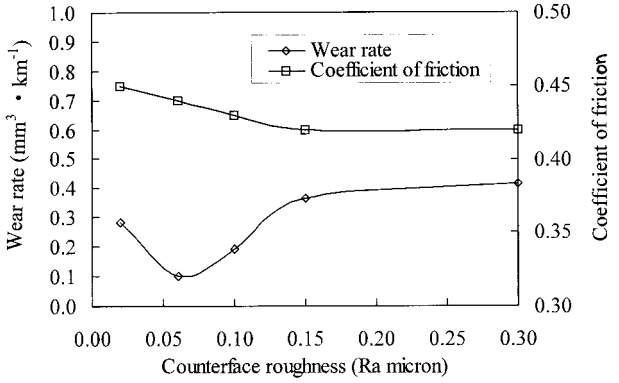

Figure 3 Steady-state wear rate and coefficient of friction versus counterface roughness (test conditions: sliding speed, 1.0 m s^{-1}; nominal pressure, 0.65 MPa).

contact area. For smoother counterface, the real contact area increased, so the coefficient of friction rose also.

To investigate the influence of counterface roughness on wear, sliding tests were performed at a sliding speed of 1.0 m s^{-1} and a nominal pressure of 0.65 MPa. Figure 2 shows the plots of wear loss versus sliding distance for five values of the initial counterface roughness. It can be seen that the influence of counterface roughness on both the transient and the steady states of wear is significant. As commonly observed, wear in the transient state start with a very high value and gradually decreased to a much lower steady-state value. The transient wear loss for any sliding distance increased with the increase of counterface roughness. The sliding distance for transition from the transient state to the steady state also increases with increasing counterface roughness.

The high wear loss at the beginning of sliding occurred because of the abrasive action of hard counterface against soft polymer. As sliding continues, more and more polymer wear debris was abraded off the polymer pin surface and was deposited in the valleys of counterface asperities. This resulted in a gradual development of polymer transfer film on the metal counterface. In other words, with increasing sliding distance in the transient state, the transfer film kept increasing until it reached a steady state of development. When this happened, the steady-state wear commenced. The wear in the steady state was lower because the hard metal asperities were now covered by the soft polymer transfer film and so the asperities were not able to abrade the polymer pin surface.

Because transient wear is terminated by the formation of a stable transfer film as discussed previously, the transition between transient and steady wear states depends on the time or sliding distance for the formation of such a transfer film. This is so because the shallower asperities on the counterface of lower surface roughness were filled up more quickly. On the roughest counterface that had the roughness of 0.30 μm Ra, the coverage of transfer film increased with increasing sliding distance; but, even after 7.0 km sliding, which corresponded to the steady state of wear, the coverage of transfer film on the counterface was not complete. The transient wear rate increased with increasing counterface roughness because of the increased abrasive action of the counterface, because the transfer film was not yet completely formed in this stage.

Figure 3 shows the plots of steady-state wear rate and coefficient of friction as a function of counterface roughness. The lowest steady-state wear rate was obtained for a counterface roughness of 0.06 μm Ra. It is higher for both higher and lower counterface roughness. This is unlike the transient state where wear rate increased consistently with increasing counterface roughness. Wear rate in the case of the counterface of 0.06 μm Ra roughness was lower because here the transfer film layer was more uniform and smooth (Fig. 4). The wear rates on the counterfaces of 0.02 and 0.30 μm Ra were fairly high. This is because the transfer film on the counterface of 0.30 μm Ra was lumpy and nonuniform (Fig. 5), whereas a good transfer film coverage was not achieved for the smoothest surface of 0.02 μm Ra (Fig. 6), since the worn polymer fragments could not be entrapped well into the shallow asperities of the

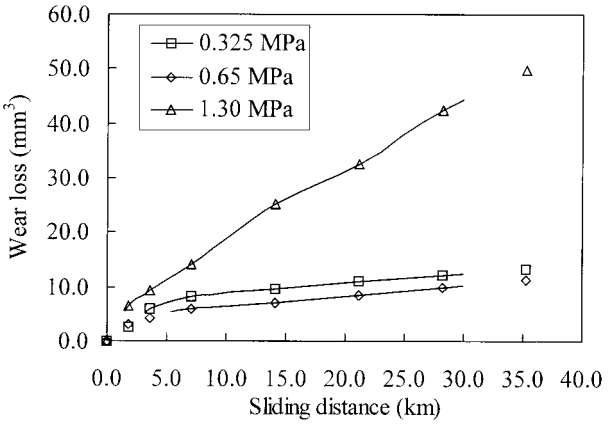

Figure 4 Wear loss versus sliding distance for different nominal pressures (test conditions: sliding speed, 1.0 m s^{-1}; counterface roughness, 0.10 μm Ra).

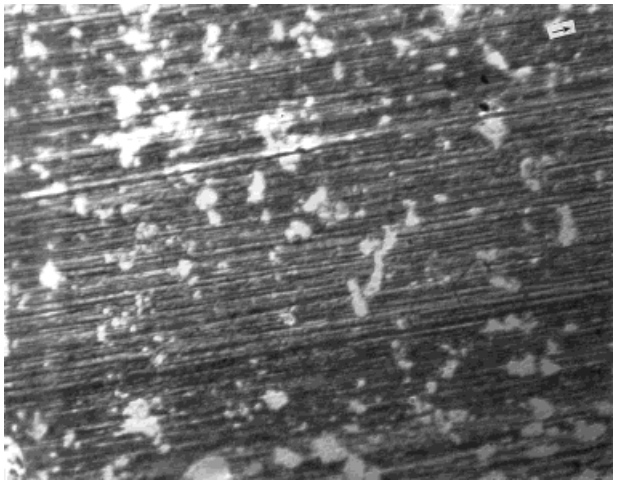

Figure 5 Optical microscope photograph of the transfer film on the counterface with a surface roughness of 0.02 μm Ra (sliding speed, 1.0 m s^{-1}; nominal pressure, 0.65 MPa; test duration, 4 h; arrow, indicates sliding direction; 320×).

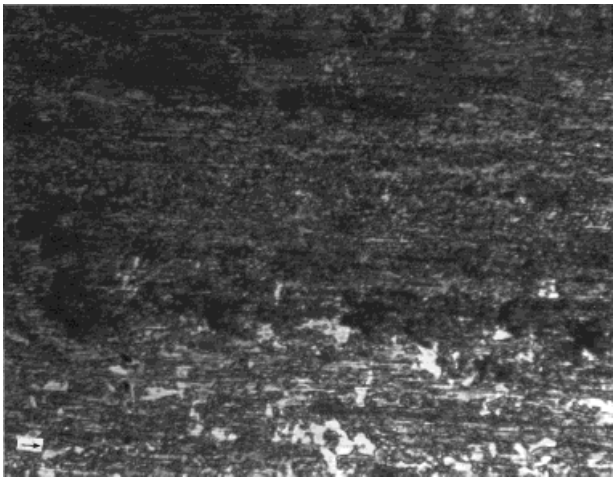

Figure 7 Optical microscope photograph of the transfer film on the counterface with a surface roughness of 0.15 μm Ra (sliding speed, 1.0 m s^{-1}; nominal pressure, 0.65 MPa; test duration, 4 h; arrow, indicates sliding direction; 320×).

disk surface. This explanation is based on the mechanism of transfer film formation discussed in an earlier article.[14] Such a transfer film was also peeled off easily by the sliding action of the pin over this surface. This contributed to wear in addition to that caused by the exposed counterface surface. In the cases of the fairly rough counterfaces, such as 0.15 μm Ra and higher, the transfer film formed was lumpy (Figs. 5 and 7). This is because of the highly abrasive action of the rougher counterface that gave rise to bigger size wear debris. Such big particles were not entrapped well into the grooves of the counterface. Thus, a thorough coverage of wear track with transfer film was again not obtained.

Effect of Sliding Speed on Wear and Friction

Figure 8 shows the variation of the coefficient of friction with sliding distance for different sliding

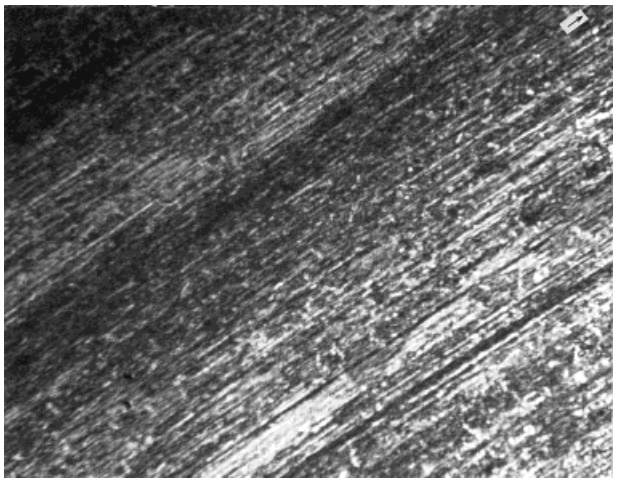

Figure 6 Optical microscope photograph of the transfer film on the counterface with a surface roughness of 0.06 μm Ra (sliding speed, 1.0 m s^{-1}; nominal pressure, 0.65 MPa; test duration, 4 h; arrow, indicates sliding direction; 320×).

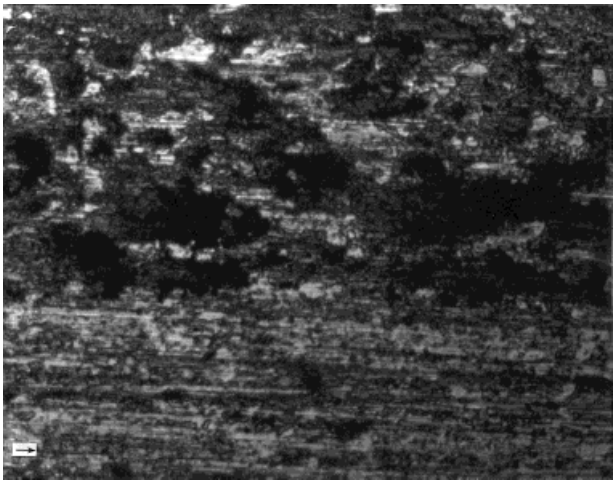

Figure 8 Optical microscope photograph of the transfer film on the counterface with a surface roughness of 0.30 μm Ra (sliding speed, 1.0 m s^{-1}; nominal pressure, 0.65 MPa; test duration, 4 h; arrow, indicates sliding direction; 320×).

speeds. The steady-state coefficient of friction data against sliding speed was plotted in Figure 9. The initial values of the coefficients of friction were about the same for all sliding speeds, but the differences became significant as sliding continued. At the low sliding speeds of 0.25 and 0.50 m s^{-1}, the coefficients of friction went down during the transient wear states and came to lower stable values at the steady state. At the medium sliding speeds of 0.75 and 1.0 m s^{-1}, the coefficient of friction went up during the transient state and reached a higher steady-state value. At the highest sliding speed of 2.0 m s^{-1}, the transient state coefficient of friction went up sharply first and then went down quickly, finally reaching the lowest steady-state value of about 0.29.

The above variation of the transient coefficient of friction with sliding speed reflects the influence of the factors governing the formation and development of transfer film. As discussed previously, the transfer films developed during the transient state at the low sliding speeds of 0.25 and 0.5 m s^{-1} were minimal. The coefficients of friction were therefore low because of low adhesion between the polymer and the metal. They were initially high because of plowing of the hard metal asperities into the softer polymer surface, but gradually went down because of some smoothening that occurred with sliding between the soft and the hard surfaces. At the sliding speed of 1.0 m s^{-1}, a uniform transfer film developed during the transient state; thus, the coefficient of friction went up and reached a higher steady-state value because of the higher cohesive forces between the PPS molecules. The same would be expected for the case of a sliding speed of 0.75 m s^{-1}. At the highest sliding speed of 2.0 m s^{-1}, initially a rapid buildup of transfer film occurred because of increased surface temperature so that the coefficient of friction increased rapidly too with increasing cohesion between the pin and the transfer film, both being of the same PPS material.

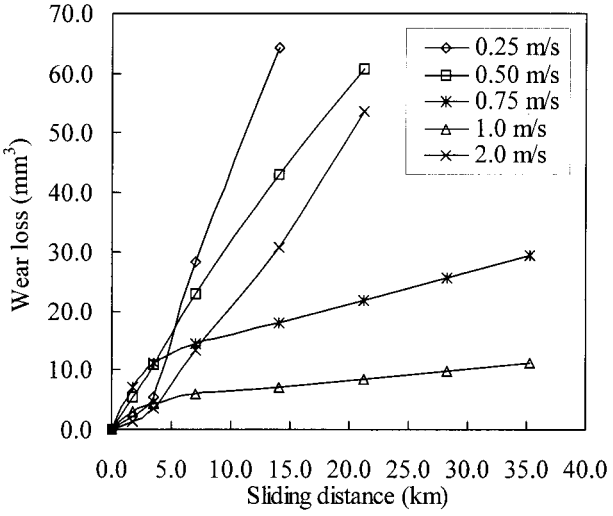

Figure 9 Wear loss versus sliding distance for different sliding speeds (test conditions: counterface roughness, 0.10 μm Ra; nominal pressure, 0.65 MPa).

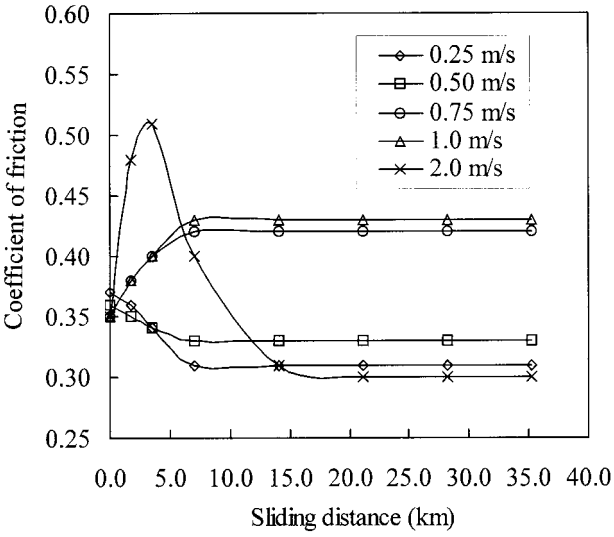

Figure 10 Coefficient of friction versus sliding distance for different sliding speeds (test conditions: counterface roughness, 0.10 μm Ra; nominal pressure, 0.65 MPa).

Figure 10 shows the variation of wear with sliding distance for different sliding speeds when the tool steel counterface with the same roughness of 0.10 μm Ra was used in all the experiments. From the curves, it is seen that transient wear can lead to either lower or higher steady-state wear, depending on the sliding conditions. In the transient state, there seems to be no order between wear rate and sliding speed. This is the result of various factors related to sliding speed, such as temperature rise, strain rate of deformation, rate of transfer film buildup, etc.

In the case of the lowest sliding speed of 0.25 m s^{-1}, wear rate was low in the early part of the transient state, presumably because of the presence of adsorbed layers on the counterface. With increased sliding, these layers were removed and so wear increased. With the increase in sliding speed, the adsorption layers present on the interface were quickly removed by frictional heating and the wear in the transient stage was higher than in the previous case. Wear thus occurred

mostly by abrasion throughout and the wear rate was again very high. At the higher sliding speed of 0.75 m s^{-1}, wear in the transient state was about the same as at 0.5 m s^{-1} for the same reasons as described above, but it was reduced to a much lower value in the steady state. This was so because the wear fragments generated were smaller in size due to higher strain rate effects and the transfer film developed and covered the counterface partially. Wear was thus no more predominately abrasive. At the sliding speed of 1.0 m s^{-1}, transfer film developed more quickly because of smaller wear particles and the transient state soon changed to the steady state. At the highest sliding speed of 2.0 m s^{-1}, transfer film developed very quickly during the transient wear state, and the uniform transfer film developed during this period was responsible for the very low transient wear.

The previous discussion on the effect of sliding speed on wear indicated that transfer film played an important role in both the transient and steady states of wear. At low sliding speeds, transfer film could not develop so that wear rate was high throughout the entire period of sliding. At high sliding speeds, frictional heat contributed to the high surface temperature resulting in softening and melting of the polymer; thus, no uniform transfer film could develop on the counterface. Consequently, wear rate was high. It was at the medium sliding speeds that a uniform transfer film developed during the early transient state so that wear rate in the later transient state and in the steady state largely decreased.

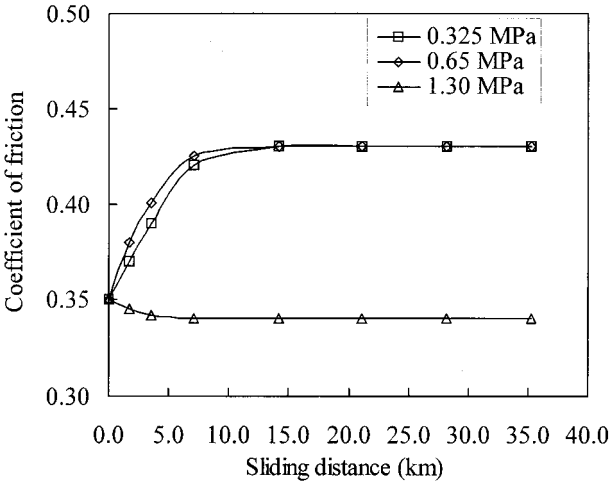

Figure 11 Coefficient of friction versus sliding distance for different nominal pressures (test conditions: sliding speed, 1.0 m s^{-1}; counterface roughness, 0.10 μm Ra).

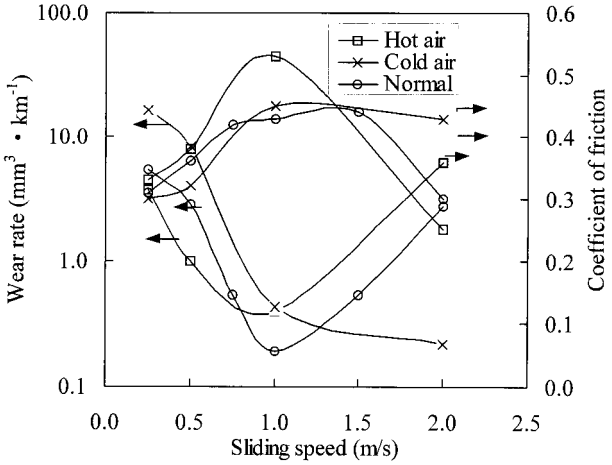

Figure 12 Steady-state wear rate and coefficient of friction versus sliding speed with the counterface heated or cooled (test condition: nominal pressure, 0.65 MPa; counterface roughness, 0.10 μm Ra).

Effect of Applied Load on Friction and Wear

Figure 11 shows the plots of the coefficient of friction versus sliding distance for three nominal contact pressures. The coefficients of friction for both 0.325 and 0.65 MPa pressures have almost identical behaviors. At the highest contact pressure, the transfer film was not able to develop during the transient state so that the coefficient of friction virtually remained unchanged with sliding distance. Because of low adhesion between the dissimilar metal and polymer materials, the steady-state coefficient of friction here was also lower than that for the lower pressures where the contact occurred between similar materials.

Figure 12 shows the plots of wear loss versus sliding distance for three nominal contact pressures where sliding was performed at 1.0 m s^{-1} against a counterface of 0.1 μm Ra roughness. The comparison of the curves for 0.325 and 0.65 MPa nominal contact pressures shows that the sliding distance needed to complete the transient state of wear is a little longer at the lower pressure, and the steady-state wear rates are almost the same in both cases: 0.18 mm^3 km^{-1} for 0.325 MPa and 0.19 mm^3 km^{-1} for 0.65 MPa nominal pressure, respectively. The higher temperature at the interface at the higher contact pressure presumably helped in promoting a rapid formation of the transfer film, thus providing good protection to

the polymer pin surfaces from the abrasive action of asperities of the counterfaces. The steady-state wear rates in both cases were thus about the same. At the higher contact pressure of 1.30 MPa, the abrasive action of the counterface asperities on the polymer pin surface was more severe, and the higher pressure also promoted a higher surface temperature. The latter presumably caused softening, and removal of the transfer film if any formed on the counterface. Consequently, the steady-state wear was very high in this case.

CONCLUSIONS

The following conclusions can be drawn:

1. The counterface roughness, sliding speed, and applied load had significant influences on the transient wear and friction of PPS. Of the three variables, sliding speed had the most profound effect. These factors also affected the steady-state friction and wear mainly through their effect on the formation of transfer film.
2. With sliding at 1.0 m s^{-1} against the counterface of 0.10 μm Ra, the transient wear for any sliding distance, as well as the steady-state wear rate, were much higher at the nominal contact pressure of 1.30 MPa than at 0.325 or 0.65 MPa. The steady-state wear rates at the lower contact pressures of 0.325 and 0.65 MPa were about the same.
3. The coefficient of friction decreased with the increase in counterface roughness from 0.02 to 0.15 μm Ra and did not change when roughness was increased to 0.30 μm Ra.
4. With sliding at a contact pressure of 0.65 MPa, the steady-state coefficient of friction was the highest at the sliding speed of 1.0 m s^{-1}.
5. With sliding at 1.0 m s^{-1}, the steady-state coefficient of friction decreased when contact pressure was increased from 0.65 to 1.30 MPa. There was no difference in the coefficient of friction in both the transient and steady states at the lower pressures of 0.325 and 0.65 MPa.
6. With the increase in counterface roughness, the wear for any sliding distance during the transient state increased, and the time for change from the transient state to steady-state wear also became longer. In this case, the transfer film also took longer time to develop. The optimal counterface roughness for minimum steady-state wear rate was 0.06 μm Ra when sliding was performed at a sliding speed of 1.0 m s^{-1} and a nominal pressure of 0.65 MPa.
7. Sliding speed influenced the transient wear in a complicated manner. At the lowest sliding speed of 0.25 m s^{-1} and the highest speed of 2.0 m s^{-1}, wear rates in the transient state were lower than in the steady state. In the sliding speed range of 0.25 to 2.0 m s^{-1}, steady-state wear was the lowest at the sliding speed of 1.0 m s^{-1} when sliding was performed against a counterface of 0.10 μm Ra at a contact pressure of 0.65 MPa. The transfer film formed in this case covered almost the entire sliding track.

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